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6. AUTHOR(S)

David C Larbalestier

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Applied Superconductivity Center
University of Wisconsin - Madison
1500 Engineering Drive
Room 909 ERB
Madison WI 53706-1609

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NE
801 N. Randolph St. Room 732
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(Attn: Dr Harold Weinstock)

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14. ABSTRACT

There is strong Air Force interest in compact, airborne, high-power generators and klystron/gyrotron/magnetron magnets for radar applications. Both applications need superconducting magnets but, to be practical, superconducting magnets must be made with high temperature superconductors (HTS) capable of being refrigerated by robust cryocoolers at temperatures near liquid nitrogen (77K). The pacing element for all such applications is the conductor from which such magnets can be made. The material of choice for this conductor is $YBa_2Cu_3O_{7-x}$, made in the form of a multilayer tape as a *Coated Conductor*. This report proposal describes research carried out in support of this effort from 1999-2002. Our global thrusts were to understand the ultimate critical current potential of YBCO in coated conductor form. To this end we performed the following work under this contract: 1. Studies of current limiting mechanisms in Coated Conductor samples., 2. Studies of the microstructure of buffer and YBCO layers of Coated Conductors, 3. Analysis of the influence of obstructions to current flow and local dissipation, and 4. Facility development in support of our research program..

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					David C Larbalestier
					19b. TELEPHONE NUMBER (include area code) (608) 263 2194

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Fundamental Studies for High Temperature Superconductor Conductor Technology

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PI: David C Larbalestier
University of Wisconsin-Madison
Applied Superconductivity Center
1500 Engineering Drive, 909 ERB
Madison, WI 53706
(608) 263 2194 phone
(608) 263 1087 fax
larbalestier@engr.wisc.edu

OBJECTIVES

Developing high critical current density (J_c) in conductors is the most essential step to developing attractive power technologies from high temperature superconductors (HTS). HTS materials possess attractively high J_c values over a large domain of temperature and field but real conductors contain many defects that limit the transport current density below their very high local values. Our goal is to understand the current limiting mechanisms of actual and prototype coated conductor (CC) forms. Two generations of conductor form are discussed today, a first generation based on $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$, which is available now in kilometer lengths, and a second generation conductor based on biaxially aligned $YBa_2Cu_3O_{7-\delta}$, which has received a proof of principle in short lengths. During 2002 came the first continuously processed lengths from industry with properties exceeding 100 A over 1 meter. This success is a result of intense effort on scaling up YBCO coated conductors in the national labs and in industry, with strong support from university programs such as this one. The central focus of our work has been to understand the way in which the connectivity determines the J_c of YBCO conductor forms. Our major effort was to use coordinated studies of the voltage-current characteristics, magneto optical imaging, microstructural analysis and theoretical study of the percolation of current around obstacles to understand the critical current density. This integrated view was then used to raise the properties of the whole conductor.

Collaboration is an essential component of our work. Some samples we make ourselves but a vital part of our work was that we received samples from many leading groups. Our work was guided by our strong linkages with the leading groups in the field at American Superconductor Corp. (ASC), ORNL, LANL, and the AFRL. This grant also provided the seed for the MURI on Fundamental Science of Coated Conductors, which started in July 2001.

SUMMARY OF WORK COMPLETED

The global thrusts of the work were to understand the ultimate critical current potential of YBCO in coated conductor form. To this end we have performed the following work under this contract:

1. Studies of current limiting mechanisms in Coated Conductor samples.
2. Studies of the microstructure of buffer and YBCO layers of Coated Conductors.
3. Analysis of the influence of obstructions to current flow and local dissipation.
4. Facility development.

1. Current limiting mechanisms

(CLM) in coated conductors have been studied primarily by Magneto optical (MO) imaging coupled with Electron Backscatter Kikuchi Pattern (EBKP) analysis and by "micro-J_c" transport measurements. This work was collaborative, being performed on AMSC, AFRL and ORNL samples. The added capability of nano-volt transport measurements to our MO facility allowed us to image RABiTS-type CC samples from both AMSC and ORNL under an applied transport current. We were able to directly show that current percolates in these conductors from well before the onset of measurable dissipation (current much less than I_c) to well after (current greater than I_c). We observed that dissipation is often quite localized, with much of the sample carrying current well below the local J_c, even at applied transport currents well above the macroscopic J_c of the entire sample. This directly demonstrated untapped potential in these conductors. The results of the MO studies led us to further examine the local J_c in these conductors via "micro-J_c" transport measurements, where links no larger than 10 x 30 μm were placed across single GBs and within single substrate grains in RABiTS-type CCs. In one sample an intra-grain J_c of 5.1 MA/cm^2 was measured in a sample with a full width J_c of only 1.2 MA/cm^2, further demonstrating that current must be percolating through these conductors. Most intra-grain J_c values measured exceeded full-width J_c values. Electron Backscatter Kikuchi Pattern (EBKP) analysis was used to measure the GB angles of the inter-grain links, and the $J_c(\theta)$ dependence observed in RABiTS-type CCs matched well with bi-crystal studies.

2. Studies of the microstructure of buffer and YBCO overlayers:

We studied the relative orientations of the underlying Ni substrate, the buffer layers, and the YBCO in a RABiTS-type CC. XRD studies of CC suggested a sharpening of the c-axis alignment in the YBCO relative to the substrate, but were not convincing. Using Electron Backscatter Kikuchi Pattern (EBKP) analysis and ion milling to remove the layers of the CC, we were able to track the changes in individual GB angles from the substrate through the buffer layers and into the YBCO. We found that there was in fact a sharpening of the c-axis alignment of the YBCO, and that this generally led to reduced GB angles in the YBCO relative to the substrate. This is a positive result, with GB angles improving by more than 1 degree on average, though some GB angles increased as well.

3. Analysis of the influence of obstructions to current flow and their influence on local dissipation:

We performed extensive calculations of current flow and dissipation around planar obstacles in coated conductors using the newly developed hodograph method, which enabled us for the first time to obtain exact solutions of the Maxwell equations using the highly nonlinear E-J characteristics of superconductors. The results show that this non-linearity of the E(J) characteristics causes significant spread of the electric field and dissipation field on scales much greater than the defect size. These features cause even sparse arrays of small obstacles to act as important current-blocking effects, significantly reducing the effective current-carrying cross-section of coated conductors. Extended hot sports of strong electric field and dissipation near planar defects can trigger thermal instabilities, which limit the current-carrying capability of coated conductors. We developed analytical formulas for the power dissipation near defects and the global average of the critical current density (i.e. that which is measured), taking into account localized electric field hot spots in a distributed array of planar obstacles. We used this to calculate the thermal runaway current, which causes local thermal instability near defects. The obtained results are in agreement with recent laser scanning microscopy and magneto-optical studies, which allow direct visualization of electric field and current distributions in coated conductors.

4. Facility Development:

A. In early 2000 we added the ability to perform *in-situ* transport measurements with a voltage resolution of < 10 nV to our MO facility. This ability allows us to directly image the self-field of a sample and hence the percolative behavior of current flow in CCs.
B. In late 2002, we purchased a new cryostat for MO imaging under an applied transport current, which when ready, will allow us to apply much higher currents and therefore study samples with larger links or higher J_c values.
C. In the middle of 2002, we added pulsed-current transport measure capability to our 14/16 T Oxford Magnet System to meet the large I_c demands of newer CCs. Using a current pulse of only 50 ms and a voltage read of 10 ms, we are able to obtain a voltage of < 50 nV. The pulsed-current system is readily expandable to 80A or more.

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